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THE RATE SENSITIVITY OF HIGH STRENGTH SYNTACTIC FOAM

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1. ABSTRACT

A series of dynamic experiments was performed on high crush strength syntactic foam to characterize how rate affects the compressive and tensile properties of the material. The investigation was carried out as part of a larger effort to develop a rate sensitive material model for sandwich composites with syntactic foam cores. Both the compressive and tensile experiments were performed on the compressive split Hopkinson pressure bar. The tensile experiments were conducted using an indirect tensile splitting, or Brazilian, test arrangement. Quasi-static experiments were also conducted in compression, tension, and shear. A comparison of the quasi-static and dynamic properties showed that syntactic foam is mildly dependent on rate in compression but unaffected by rate in tension. The shear experiments showed that bond between a syntactic foam core and composite face sheets could be a weak link in a sandwich design. The syntactic foam, Eccofloat-TG-24A, was manufactured by Emerson & Cuming.

2. INTRODUCTION

The use of sandwich composites in naval applications has increased dramatically in recent years. Low-density foams have traditionally been used as the core material of choice in commercial naval applications. The core materials in military applications must be much more rugged than their commercial counterparts due to the need to withstand extreme shock loading and sometimes harsh environments. The high crush strength and low density of syntactic foam makes it an ideal core material for sandwich composites used in military applications.

Historically, syntactic foam has been used in relatively simple buoyancy applications that required knowledge of only the static crush strength and elastic modulus. The use of syntactic foam as a core material in complex structures that could potentially be subjected to shock waves demands more detailed knowledge of material properties. If an explosion occurs near a naval vessel a compressive shock wave is generated. As the initial compressive shock wave hits a structure it can be reflected as a tensile wave within the structure. The initial shock wave can also cause a structure to bend or flex which in turn would cause the core of a sandwich to be stressed in shear. The post yield behavior of syntactic foam is important for crash and battle damage analyses.

The compressive split Hopkinson pressure bar (SHPB) was used to conduct dynamic compressive and tensile experiments. Gomez et al. showed that the tensile splitting, or Brazilian, test arrangement could be used on the compressive SHPB to determine tensile properties of brittle materials such as rock or granite [1]. Even though syntactic foam is not brittle, the tensile splitting arrangement was chosen because epoxy was not required to bond the tensile splitting specimen to the compressive SHPB bars. The tensile SHPB arrangement required epoxy. In addition, the tensile splitting specimen is simpler than a tensile SHPB specimen.

The syntactic foam that was tested in this paper was manufactured by Emerson & Cuming under the brand name Eccofloat-TG-24A. The “24” in the brand name designates a nominal density of 24 lbs/cu. ft. (0.38 g/cc). Emerson & Cuming lists the static crush strength of Eccofloat-TG-24A at 20.68 MPa (3000 psi) and the elastic modulus at 1241 MPa (180 ksi). The Emerson & Cuming syntactic foam was chosen for investigation because the density to crush strength ratio of the Eccofloat line was superior to similar products.

3. EXPERIMENTAL PROCEDURES

3.1 Quasi-Static Experiments

All quasi-static experiments were carried out using an Instron model 1125 with a 90000 N load cell. The load applied to the specimen, P , was recorded during all of the static experiments.

3.1.1 ASTM-D-695 Compressive Experiments

In order to determine the compressive elastic modulus, compressive Poisson’s ratio, and compressive failure stress of Eccofloat-TG-24A six specimens were tested according to ASTM-D-695 [2]. The specimens had a 1.27 x 1.27 cm (0.5 x 0.5 in.) square cross-section and were 5.08 cm (2 in.) long. Strain gauges were used to determine ϵ_{xx} and ϵ_{yy} on the faces of the sample. The specimens were crushed between two steel platens. Oil was used to lubricate the platen/specimen interface.

3.1.2 Compressive Experiments to Determine Post Yield Behavior

Thin disks were tested to determine the quasi-static post yield behavior of syntactic foam. Five 0.279 cm (.11 in) thick and 0.953 cm (0.375 in.) diameter disks were tested. Eight additional 0.610 cm (0.24 in.) thick and 2.22 cm (0.875 in.) diameter disks were also tested. The test specimens were crushed through the thickness between two platens. Oil was used to lubricate the platen/specimen interface. These samples were used to determine post yield behavior because the ASTM-D-695 samples split open shortly after the onset of crushing leading to a rapid decrease in load carrying capability.

3.1.3 ASTM-D-638 Tensile Experiments

In order to determine the tensile elastic modulus, tensile Poisson’s ratio, and tensile failure stress of Eccofloat-TG-24A six dog bone specimens were tested according to ASTM-D-638 [3]. Figure 1 shows the dimensions of the ASTM-D-638 dog bone specimen that was used. The gauge length and tab area of the dog bone was made larger

than the typical ASTM-D-638 specimen to help assure that the sample failed in the middle. Tabs made from G10 composite were also glued to the ends of dog bone to reduce the local effects of the grips and help assure that dog bone did not fail near the ends. Strain gauges placed at the center of the specimens were used to determine ϵ_{xx} and ϵ_{yy} .

3.1.4 Tensile Splitting Experiments

Brazilian tensile tests, or tensile splitting tests, were performed on four 2.22 cm (0.875 in.) diameter, 0.476 cm (0.188 in.) thick specimens. The test sample was placed on edge and crushed between two platens. Brazilian tensile tests are based on standard elasticity theory. The two-dimensional stress field in the disc can be derived with elasticity theory and then simplified to examine only the stress along the loading line [4]. Taking into account the specimen thickness, L , the stress distribution for the Brazilian splitting test is given by Equation 1, with parameters defined in Figure 2 [5].

$$\sigma_y = \frac{2P}{\pi LD} \left[\frac{D^2}{y(D-y)} - 1 \right] \quad (1a)$$

$$\sigma_x = \frac{2P}{\pi LD} \quad (1b)$$

As shown, a constant tensile stress, σ_x , is generated along the loading line. At the contact points the elasticity solution is no longer valid due to the singularity of the loading. At these points there exists a bi-axial compressive stress of equivalent levels which allow the specimen to fail in tension along the loading line and not locally by compression. Brittle materials with a relatively low tensile strength compared to their compressive strength, will tend to fail in tension along the loading line. For each of the splitting tensile experiments the maximum load, P , was used to calculate the splitting stress, σ_x , at failure using Equation 1b.

The static tensile splitting tests were performed to generate a direct comparison to the dynamic tensile splitting experiments described later in this work. The ASTM-D-638 dog bone is superior for determining the tensile strength of syntactic foam because it the stress field created is more uniformly tensile in nature.

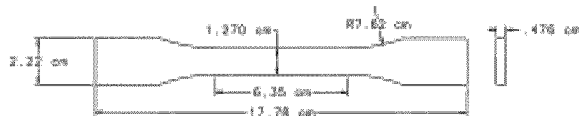


Figure 1: ASTM-D-638 dog bone specimen.

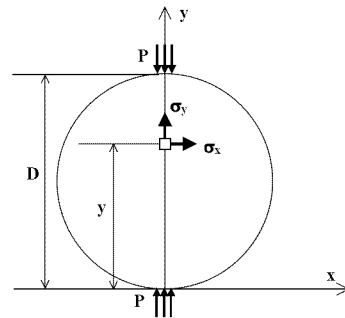


Figure 2: Tensile-Splitting Test Schematic

3.1.5 Shear Test Per ASTM-D-3528-96

Tensile tests using double lap shear specimens were performed according to ASTM-D3528-96 in an attempt to determine the shear strength of syntactic foam [6]. A picture of the ASTM-D3528-96 double lap shear specimen is shown in Figure 3. The following four types of adhesives were used to bond the syntactic foam to S2 glass face sheets of the double lap shear specimen: Hysol 9309.3NA, Emerson & Cuming, Plexus MA310, and West 105/206. Combinations of degreasing, sanding with 80 grit sand paper, and priming, were used to prepare the syntactic foam samples.

3.2 Dynamic Experiments

3.2.1 Dynamic Compressive Experiments

A series of compressive SHPB experiments were performed at various strain rates in order to determine the dynamic compressive stress/strain response of the syntactic foam. The compressive SHPB setup is shown in Figure 4. The cylindrical specimens were sandwiched between the incident bar and the transmitter bar with a thin coating of lubricant on each face of the specimen to reduce frictional effects. The incident bar was impacted with a 30.48 cm (12 in.) long, 1.27 cm (0.5 in.) diameter aluminum projectile fired from a gas gun. The projectile impact creates a compressive wave that travels down the incident bar and into the specimen. A portion of the wave is transmitted through the specimen into the transmitter bar, and the rest is reflected back into the incident bar. Strain gages on the two bars measure the incident, transmitted, and reflected waves and the signals are recorded using a LeCroy Model 8025 high-speed data acquisition system.

The dynamic stress-strain response of the specimen can be obtained using the recorded incident, transmitted, and reflected strain wave histories using the theory of one-dimensional wave propagation [6]. Assuming that the specimen deforms uniformly and is in equilibrium, the stress (σ_s) and strain (ϵ_s) in the specimen as a function of time can be generated from the reflected (ϵ_r) and transmitted (ϵ_t) strain signals using the relations given in Equations 2, 3, and 4.

$$\epsilon_s(t) = \frac{-2c_b}{l_s} \int_0^t \epsilon_r(t) dt \quad (2)$$

$$c_b = \sqrt{\frac{E_b}{\rho_b}} \quad (3)$$

$$\sigma_s(t) = E_b \frac{A_b}{A_s} \epsilon_t(t) \quad (4)$$

where A_b and A_s are the cross-sectional areas of the bar and specimen respectively, l_s is the specimen length, c_b is the wave speed in the bar material, and E_b and ρ_b are the Young's modulus and density of the bar material, respectively.

For the specimen to reach a state of equilibrium, a relatively long incident pulse as compared to the specimen length is required. The long pulse allows for multiple wave

reflections with in the specimen, ensuring the loads on the incident and transmitter faces of the specimen, P_1 and P_2 , respectively, are equal at the time of failure. The loads can be calculated using Equations 5 and 6 where ε_i , ε_r , ε_t are the incident, reflected, and transmitted strain pulses shifted in time to account for the mid-bar location of the strain gages.

$$P_1 = A_b E_b (\varepsilon_i + \varepsilon_r) \quad (5)$$

$$P_2 = A_b E_b \varepsilon_t \quad (6)$$

3.2.2 Dynamic Tensile-Splitting Experiments

The same SHPB apparatus that was used for the compressive experiments was employed in order to perform the dynamic tensile splitting experiments. However, instead of sandwiching the specimen lengthwise, the specimen was held diametrically between the bars as shown in Figure 5.

For specimens in compression, the SHPB analysis assumes that the load on each specimen face is equal, so that the specimen is in equilibrium. With this assumption the specimen stress/strain response can be calculated with Equations 2, 3, and 4. However, the standard analysis cannot be used to obtain the specimen stress for the dynamic splitting experiments.¹ For tensile splitting experiments the peak tensile-splitting stress of the specimen is assumed to be proportional to the peak transmitted compressive strain measured in the transmitter bar given by Equation 5, and that the load P is now defined by Equation 6. Six tensile splitting experiments were conducted with 3.78 cm thick and 2.22 cm diameter disks.

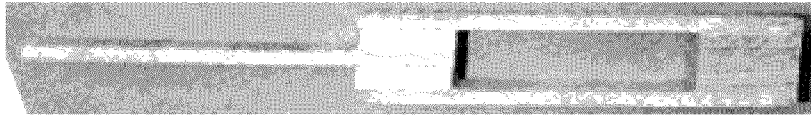


Figure 3: Double Lap Shear Specimen

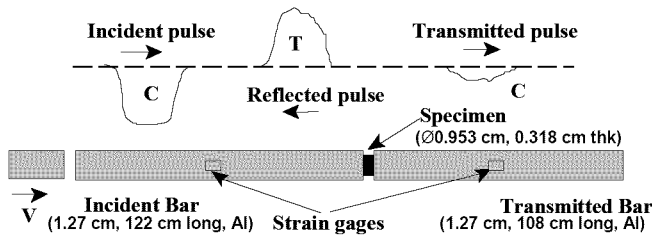


Figure 4. Compressive SHPB setup.

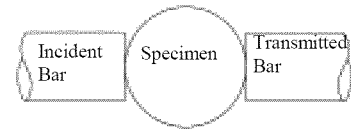


Figure 5: Brazilian SHPB setup.

4. RESULTS AND DISCUSSION

The results of the static ASTM-D-695 compression test and the static ASTM-D-638 dog bone tension tests are given in Table 1. All of the test specimens failed as expected. The compressive samples crushed and then split shortly there after. The tensile specimens failed in the middle. Examination of the failed specimens showed that the glass bubbles crushed in compression while the bubbles pulled out of the matrix in tension. The difference in failure mode explains why the static tensile failure stress was 131% smaller than the compressive static crush strength. The fact that glass behaves differently in compression and tension was probably a contributing factor to the 15% difference in the compressive and tensile elastic moduli.

The mechanical properties of syntactic foam are linearly related to density. Emerson & Cuming gives a tolerance on density of ± 0.03 g/cc (± 2 lbs/cu. ft.). The values quoted by Emerson & Cuming were for the samples on the low end of the density range. The samples tested in this work had an above average density at .393 g/cc (24.8 lbs/cu. ft.) This separation in density contributed to the measured static crush strength and compressive elastic modulus being 40% and 60% higher than the manufacture listed value respectively.

Typical static and dynamic stress strain curves from crushing syntactic foam disks are shown in Figure 6. After an initial elastic loading, the syntactic foam reached a yield point followed by a small, rapid drop in stress. After the drop the syntactic foam behaved as a perfectly plastic material over a long flat plateau until a rapid rise in stress indicated that the disk was approaching its solid height. The transition from the loading plateau to the stiffer “bottomed out” behavior occurred much sooner in the dynamic sample than in the quasi-static sample. Typical strain measurements in the transmitter and incident bar are shown in Figure 7. Equilibrium was obtained early in the strain curve loading cycle as required by the compressive SHPB theory.

All of the stress strain curves that were obtained from the dynamic crushing of syntactic foam disks are shown in Figure 8. The loading plateaus shown in Figure 7 maintained an approximate level of 31.5 MPa between 5 and 35 % strain regardless of the rate to which the samples were tested. However, as can be seen in Figure 6, the loading plateau did under go a transition between a quasi-static loading rate and lowest strain rate that could be obtained with the SHPB apparatus, 1419/s. The average loading plateau stress for the dynamic experiments was approximately 30% higher than the static average value for the smaller disks. The average loading plateau value between 5 and 35% strain for all of the quasi-static compression experiments performed on small disks are given in Table 2. The average loading plateau value did not change with the size of the disk under test and was very repeatable.

The yield points of the dynamic compression experiments are plotted against rate in Figure 9. The regression line shown in Figure 9 has a slope of 32.2 MPa/s. With this slope there is only a 16% rise in yield between 1000/s and 6500/s, which is only a marginally significant increase. However, there is a very significant transition from the

quasi-static behavior and the dynamic behavior, even for samples tested at low strain rates. The average quasi-static yield point, 25.76 MPa, was 33% higher than the lowest yield point recorded during the dynamic experiments. The yield points for all static and dynamic compression experiments conducted with small disks are listed in Table 2. It should be noted that the yield point for the Ø0.953 cm diameter disks were approximately 12% lower than both the Ø2.22 cm disks and the ASTM-D-695 experiments. The average quasi-static loading plateau level of both the larger and smaller disks were essentially equal.

When subjected to the tensile splitting load, the ends of the disks were flattened at the point of load application. The disk did eventually split however. The flats were typically 1.27 cm (0.5 in.) wide and 0.189 cm (0.0745 in.) deep. The average static splitting strength was 9.8 MPa as calculated with Equation (1b). Six dynamic splitting experiments are shown in Figure 11. The dynamic splitting strength was approximately equal to the static splitting strength. Loading rate is typically linearly proportional to the pressure behind the projectile in the gas gun. However, in this case the samples split at exactly the same time regardless of the pressure in the gas gun. Since the samples also split at approximately the same stress level, the loading rate was the same for all six samples. While unusual, the tensile splitting experiments clearly show that syntactic foam was not at all dependent on rate in tension.

The results of the ASTM-D-3528-96 double lap shear tests are given in Table 3. Shear failure of the core was not induced in any of the samples. All of the samples failed at the core adhesive interface. That is, all of the adhesive remained attached to the S2 glass face sheets after failure. The adhesive failure was most likely due to a combination of a poor bond between the core and adhesive and peeling of the face sheet from out of plane loads generated by flexure and misalignment of the face sheets. Of the four types of glue West 105/206 had the highest average failure stress of 3.56 MPa (516.4 lbf), but the large amount of scatter in the data means that West 105/206 cannot be assumed to be the best adhesive. The true shear strength of Eccofloat-TG-24A is likely on the order of 10.3 MPa (1500 psi). Additional work must be done to determine the true shear strength of syntactic foam and to find an adhesive system that can survive up to shear failure in the core.

Sample #	ASTM-D-695 Compression			ASTM-D-638 Tensile		
	Elastic Modulus (MPa)	Poisson's Ratio	Failure Stress (MPa)	Elastic Modulus (MPa)	Poisson's Ratio	Failure Stress (MPa)
1	1875	0.317	28.59	1866	0.334	11.34
2	2013	0.339	28.42	1781	0.273	9.122
3	2101	0.312	29.37	1664	0.259	13.69
4	2026	0.340	29.43	1722	0.275	12.81
5	2049	0.320	28.83	1727	0.272	14.13
6	2000	0.337	28.44	1725	0.277	13.95
Ave.	2011	0.327	28.85	1748	0.334	12.51

Table 1: ASTM-D-695 compression testing and ASTM-D-638 tensile testing.

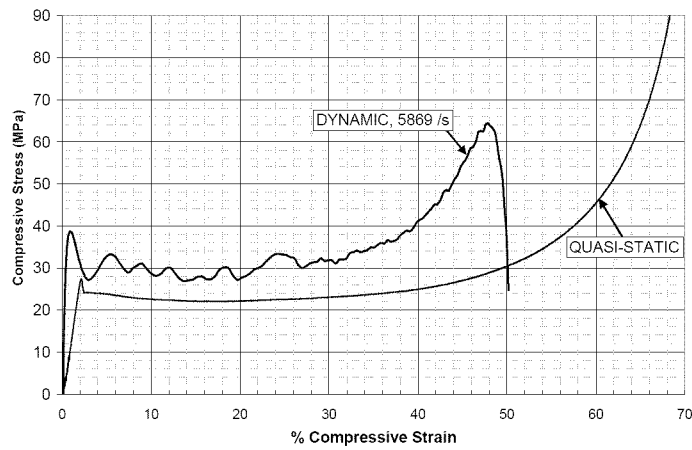


Figure 6: Typical quasi-static and dynamic Stress strain curves.

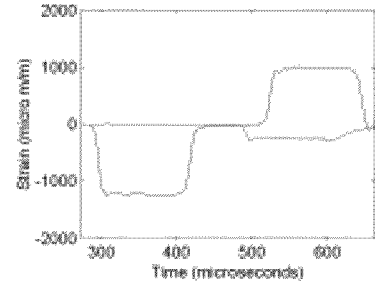


Figure 7: Typical incident and transmitter bar

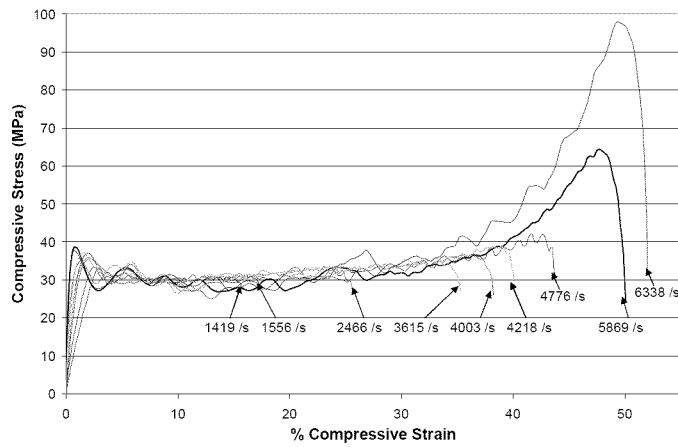


Figure 8: SHPB test of syntactic foam disks in compression.

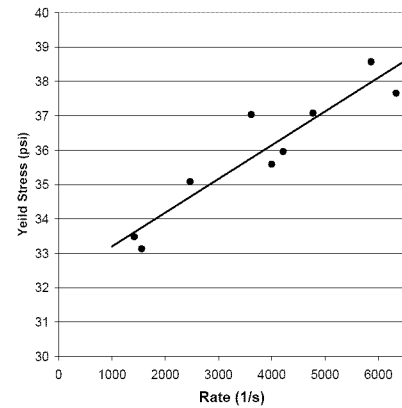


Figure 9: Static tensile splitting yield stress.

Sample #	Quasi-Static Compression of Ø0.953 cm Disks			Quasi-Static Compression of Ø2.22 cm Disks			Dynamic Compression of Ø0.953 cm Disks	
	Yield Point (MPa)	Ave. Plateau Stress (Mpa)	Min. Plateau Stress (MPa)	Yield Point (MPa)	Ave. Plateau Stress (Mpa)	Min. Plateau Stress (MPa)	RATE (1/s)	Yield Point (MPa)
1	24.34	24.41	23.55	28.79	24.27	23.90	1419	33.48
2	26.93	24.64	24.56	28.88	24.91	24.62	1556	33.13
3	25.24	23.99	23.66	28.57	23.81	23.46	2466	35.08
4	25.54	23.10	22.56	28.24	23.47	23.25	3615	37.03
5	26.74	25.00	24.53	28.13	24.41	23.55	4003	35.59
6	-	-	-	27.28	24.64	24.56	4218	35.96
7	-	-	-	27.33	23.99	23.66	4776	37.08
8	-	-	-	26.89	22.31	21.98	5869	38.57
Ave.	25.76	24.23	23.77	28.01	23.98	23.62	6338	37.66

Table 2: Static crushing of syntactic foam disks in compression.

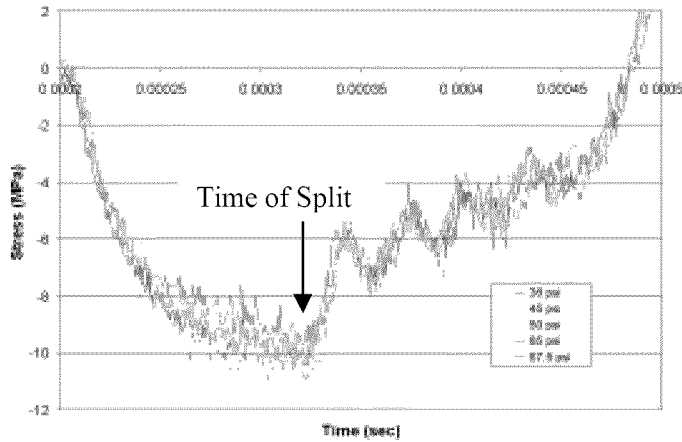


Figure 10: Dynamic tensile splitting experiments.

ID	Max Load (N)	Double Lap Area (mm ²)	Failure Stress (MPa)	Adhesive	Core Preparation
1A	4559	1265	3.61	Hysol 9309.3NA	Degrease
2A	5783	1280	4.52	Hysol 9309.3NA	80 grit Sand & Degrease
3A	3781	1281	2.95	Hysol 9309.3NA	80 grit Sand & Degrease
4A	3559	1277	2.76	Hysol 9309.3NA	80 grit Sand & Degrease
5A	2669	1277	2.09	Hysol 9309.3NA	80 grit Sand, Degrease & Prime
6A	3114	1270	2.45	Hysol 9309.3NA	80 grit Sand, Degrease & Prime
7A	3781	1279	2.96	Hysol 9309.3NA	80 grit Sand, Degrease & Prime
Mean A:			3.05		
1B	3336	1290	2.59	E&C	80 grit Sand & Degrease
2B	4003	1277	3.13	E&C	80 grit Sand & Degrease
3B	3447	1277	2.70	E&C	80 grit Sand & Degrease
Mean B:			2.81		
1C	3114	1290	2.41	Plexus MA310	80 grit Sand & Degrease
2C	3114	1290	2.41	Plexus MA310	80 grit Sand & Degrease
3C	1446	1283	1.13	Plexus MA310	80 grit Sand & Degrease
Mean C:			1.98		
1D	5560	1303	4.27	West 105/206	80 grit Sand & Degrease
2D	3559	1290	2.76	West 105/206	80 grit Sand & Degrease
3D	4671	1277	3.66	West 105/206	80 grit Sand & Degrease
Mean D:			3.56		

Table 3: Lap shear Test Results

5. CONCLUSIONS AND SUMMARY

- The compressive strength and compressive elastic modulus of the Eccofloat-TG-24A were considerably better than the values listed by the manufacture.
- The tensile strength and tensile elastic modulus were considerably less than the compressive strength and tensile strength of Eccofloat-TG-24A.
- The compressive yield strength of Eccofloat-TG-24A jumped by 33% above the quasi-static value at a strain rate of 1419/s. The compressive yield strength increased at a rate of 32.2 MPa/s above this strain rate.
- After yield Eccofloat-EG-24A behaved like a perfectly plastic material until its solid height was reached. The plastic loading plateau jumped by 30% over the

quasi-static value at a strain rate of 1419/s. The loading plateau level did not increase with an increase in strain rate.

- Eccofloat-EG-24A was not dependent on rate in tension.
- Additional experiments must be performed to determine the static and dynamic shear strength of syntactic.
- The method of forming a strong bond between syntactic foam and S2 fiberglass must be found.

6. ACKNOWLEDGEMENTS

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